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An Approach to Noise Reduction in Human Skin Admittance Measurements

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Abstract- **This paper presents the development of a signal averaging algorithm for recovering excitation responses contaminated by overwhelming amount of various types of interference in skin admittance measurements. The algorithm is designed to eliminate Gaussian-distributed noise by use of a recursive approach. The process of recovering low magnitude voltage responses from highly noise-contaminated waveforms is a CPU-intensive task. In real-time measurements, iterative reconstruction algorithm is inefficient and time consuming when slow varying input waveforms are present. To increase the quality of the reconstruction a considerably large number of recursions is required. Increasing the number of recursions is appropriate for batch processing of measurement data. However, the algorithm considers measurements in real-time, whereas required quality of signal reconstruction should be kept independent from the number of recursions**.

I. INTRODUCTION

For medical measurement systems choosing appropriate filter specifications is not always a straightforward process. The difficulty generally arises from insufficient knowledge of the unknown signal power spectrum and the noise power spectrum. The major difficulty arises when noise signal is randomly occurring with a wide frequency range that overwhelms the frequency range of the measured signal. In this case the type of filter implementation is a dominant part of the overall system design. Signal averaging provides excellent results for noise removal, when the signal is corrupted by additive white Gaussian noise. Recently, there have been many attempts to improve the denoising performance at small sample sizes by using statistical inference methods based on wavelet statistical models and Bayesian estimation [11,12]. The proposed algorithm is rather different and will efficiently increase the S/N ratio by averaging out the unwanted signal, even with very low level of input signal amplitudes.

II. MEASUREMENT SETUP

Measurements were performed by simultaneous recording of dry skin parameters. The skin parameters of interest, as described in [2], are D.C potential, A.C conductance, capacitance, and the changes in these caused by the reflex. A.C measurements were performed by applying low amplitude sinusoidal in the frequency range of 0.1-1000 Hz. The measurement circuit is based on three-electrode system [7] with constant current, which were designed to record simultaneous individual measurement of electrodes. The measurement responses at different frequencies were A/D converted and recorded for denoising process by use of the averaging algorithm.

III. METHOD

Signal averaging is often done by a dedicated computer after A/D conversion. However, averaging requires that a large number of bits per unit time be processed. This, in turn, requires a fast A/D conversion and CPU-intensive digital data processing. The measurement system was simulated with several different system configurations, and several optimum results were achieved. By repetitive additions of waveforms, random noise samples tend to average to zero while the amplitude of the desired signal increased with decreasing system bandwidth and performance. It is assumed that the random noise signal must not be correlated with the desired signal. Overlapping frequency components are not cut off, on the contrary, they are manipulated equally, i.e., increased in amplitude along with the input signal.

In order to eliminate the random noise samples efficiently, it was necessary to increase the number of additions. This reduces the system bandwidth unduly and causes unstable conditions. To overcome such situations, additional operations have been applied in parallel with the averaging process. Fig. 1 illustrates an extreme situation, where a 256-samples waveform with a S/N ratio of 1/100 is given as the input.

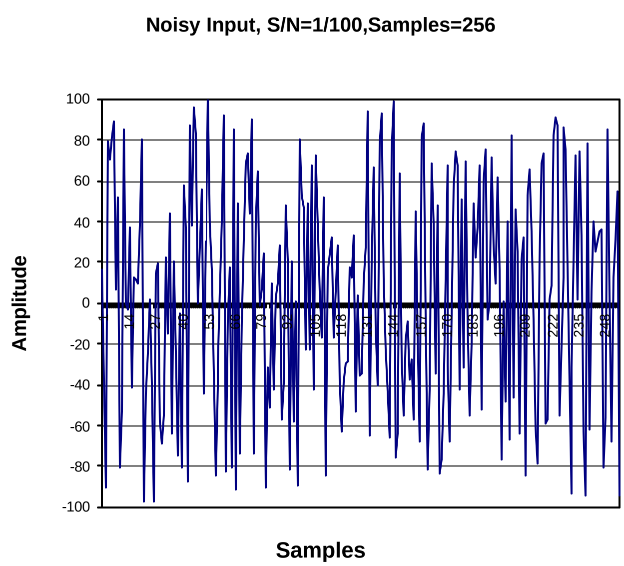

Fig. 1 Noise corrupted waveform with 256 samples and S/N ratio of 1/100.

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The output waveform after averaging process is shown in Fig. 2, which shows that the averaging has its superficial result, in which extreme spikes of random noise have vanished satisfactorily only after 50.000 recursions.

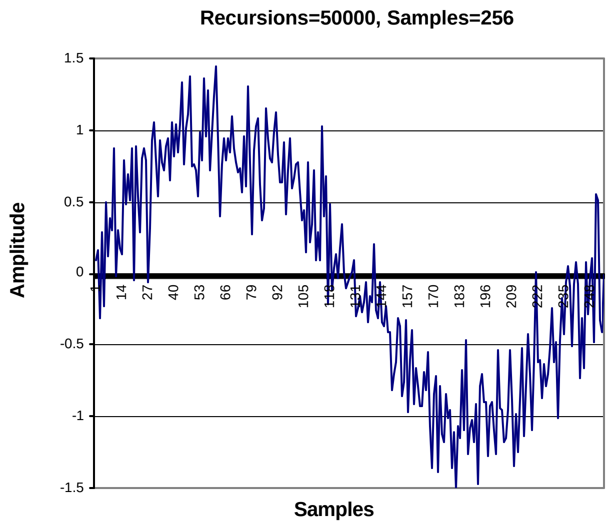

Fig. 2 Averaged waveform of the noise corrupted waveform with 256 samples. The corrupted waveform is nearly reconstructed after 50.000 iterations.

IV. APPROACH

Let T denote the time for each waveform, and if M waveforms of the noise-contaminated signal, each of duration T will be averaged, N samples from each waveform must be taken and stored, giving $M \times N$ samples in total, then a synchronized addition of the samples can be performed to produce the average value of the M waveforms. The addition of the samples can be exactly synchronised if the ith sample of the first waveform (w_1) is taken at time t_0, the ith sample of the second waveform (w_2) taken at time $t_0 + T$, and the ith sample of the Nth waveform (w_n) taken at time $t_0 + NT$. As shown in the following Mathematica code slice, each waveform (w_i) is an *observed sample* denoting a waveform of a periodic signal containing N discrete random noise and measured signal samples.

```
NoiseSamp/: NoiseSamp[magn_]:= magn*Random[Real,{-1,1}]
InpSamp/: InpSamp[sampno_Integer,n
      magn_,samps_Integer,freq_:1,Phase_:0] :=
      N[Sin[2 Pi(sampno*freq+Phase)/samps],7]+NoiseSamp[nmagn]]
```

This function is a symmetrical implementation of a waveform of which the half period is calculated by,

$$\vec{w} = \sum_{i=1}^{N} (s_{(i)} + n_{(i)})$$

Where, $s_{(i)}$ denotes the signal sample, $n_{(i)}$ the noise sample of a random magnitude, and $\vec{w}$ denotes sum of these quantities.

Corresponding samples from each waveform are then averaged to give the average value $\overline{w}_k$ at the kth sample position of M waveforms

$$\overline{w}_k = \frac{1}{M} \sum_{r=1}^{M} w_{(n,r)} \qquad 1 \le n \le N \qquad (1)$$

where $w_{(n,r)}$ represents the nth sample of the rth waveform. In the simplest manner, the average value is calculated by adding the waveforms $w_1, \ldots, w_M$ in a sample-by-sample manner, and then dividing the sum by the number of waveforms:

$$\bar{y}_{(N,M)} = \frac{1}{M} \sum_{r=1}^{M} w_{(n,r)} \qquad n = 1, \ldots, N$$

$$\bar{y}_{(N,M)} = \frac{1}{M} \sum_{n=1}^{N} \sum_{r=1}^{M} w_{(n,r)} \qquad (2)$$

where

- $w_{(n,r)}$ = nth sample of the rth waveform,
- $\bar{y}_{(N,M)}$ = Average value of M waveforms containing N samples each.

The algorithm was first implemented and tested by using the following Mathematica code slice:

```
Avr/: Avr[samples_Integer,recursions_Integer,
NoiseLvl_,Frq_:1,Phase_:0] :=
Block[{n = 0,r = 0, myi, iterator = 0,i, S,
 FilteredWave, Signalin}, Array[W,samples];
 InPut=Table[InpSamp[i,NoiseLvl,samples,Frq,Phase],
                {i,0,samples -1 }];
 Signalin = Table[InpSamp[i,0,samples,Frq,Phase], {i,0,samples - 1}];
 For [r=1, r <= recursions, r++, For [n=0, n < samples, n++,
     W[n]=W[n]+(InpSamp[n,NoiseLvl,samples,Frq,Phase]  - W[n])/r];
   iterator++;
   If[Mod[iterator,10] == 0,
      S=Table[W[myi], {myi,0, samples  - 1}];
   ] ];
 FilteredWave=Table[W[myi], {myi,0, samples - 1}];
 Return [FilteredWave] ]
```

The $M \times N$ noisy samples are grouped into *random samples* to create a *random space* of M observable waveforms defined as

$$W_1 = x_{(1,1)}, \ldots, x_{(1,N)}$$

$$W_2 = x_{(2,1)}, \ldots, x_{(2,N)}$$

$$\vdots$$

$$W_M = x_{(M,1)}, \ldots x_{(M,N)}$$

$$\begin{pmatrix} W_1 \\ W_2 \\ \vdots \\ W_M \end{pmatrix} = \begin{pmatrix} x_{(1,1)} \cdots x_{(1,N)} \\ x_{(2,1)} \cdots x_{(2,N)} \\ \vdots \\ x_{(M,1)} \cdots x_{(M,N)} \end{pmatrix} \qquad (3)$$

or arranging the waveforms into N random observable columns

$$S_1 = \begin{pmatrix} x_{(1,1)} \\ x_{(2,1)} \\ \vdots \\ x_{(M,1)} \end{pmatrix}, \cdots, S_N = \begin{pmatrix} x_{(1,N)} \\ x_{(2,N)} \\ \vdots \\ x_{(M,N)} \end{pmatrix} \qquad (4)$$

Thus, the average value of the random observable columns can be determined as

$$\bar{s}_1 = \frac{1}{M}\sum_{r=1}^{M} x_{(r,1)}$$
$$\bar{s}_2 = \frac{1}{M}\sum_{r=1}^{M} x_{(r,2)}$$
$$\vdots$$
$$\bar{s}_N = \frac{1}{M}\sum_{r=1}^{M} x_{(r,N)} \qquad (5)$$

It is obvious that the mean values $\overline{S}_1, \cdots, \overline{S}_N$ construct the *sample mean* of the M waveforms, $W_1, \cdots, W_M$ i.e.,

$$\overline{W} = \{\overline{S}_1, \overline{S}_2, \cdots, \overline{S}_N\}$$

$$\overline{W} = \frac{1}{M}\begin{pmatrix} \sum_{r=1}^{M} W_{(r,1)} \\ \sum_{r=1}^{M} W_{(r,2)} \\ \vdots \\ \sum_{r=1}^{M} W_{(r,N)} \end{pmatrix} \qquad (6)$$

A rather intuitive alternative of determining the *sample mean* $\overline{W}$ may be acquired by taking average of each waveform as a whole, and measuring the mean value of the averaged waveforms. Thus, for the M waveforms

$$\overline{W} = \frac{1}{M}\sum_{r=1}^{M} W_r \qquad (7)$$

will yield the average value, and the consequent averages for each waveform with n samples each, i.e.,

$$W_i = \{ w_1, w_2, \cdots w_n \}$$
$$\overline{W_i} = \frac{1}{N}\sum_{n=1}^{N} x_n \qquad (8)$$

Recursive additions of M waveforms with N discrete samples will yield

$$\overline{W}_r = \frac{1}{M}\sum_{r=1}^{M} W_{r-1}$$
$$\overline{W} = \frac{1}{N}\sum_{n=1}^{M} W_{(n,r)} \qquad n = 1, \cdots, N \qquad (9)$$
$$\overline{W}_{r+1} = \frac{1}{M}\sum_{r=2}^{M} \left(W_{(n,r)} + \overline{W}_{(n,r-1)} \right)$$
$$\overline{W} = \frac{1}{M}\sum_{r=1}^{M} \left(x_{(n,1)} + \cdots + x_{(n,M)} \right)$$
$$\overline{W} = \frac{1}{M}\sum_{r=1}^{M} x_{(n,r)} \qquad n = 1, \cdots, N$$
$$\overline{W} = y_{(N,M).} \qquad (10)$$

V. Conclusions

Sample-by-sample addition of two discrete-time signals derived as

$$Y_{(n,r)} = X_{1(n,r)} + X_{2(n,r)} \qquad (11)$$

where

- $Y_{(n,r)} =$ Sum output of the n[th] sample at the r[th] recursion,
- $X_{i(n,r)} =$ n[th] input sample of the discrete-time signal $w[n]$ at the r[th] recursion.

Generally, for M recursions the output sum is written as

$$Y_{(N,M)} = \sum_{r=1}^{M} \left(w_{1(n,r)} + w_{2(n,r)} \right) \qquad n = 1, \cdots, N \qquad (12)$$

However, repetitive additions of discrete-time samples have produced undesired output levels, which might be difficult to manipulate by electronic circuits. Increased number of recursions can cause noticeable degradation in system dynamics. We have therefore introduced an appropriate expression in order to keep the output under control. When the interference was high and thousands of iterations were required the control mechanism operated well. Therefore, this algorithm applies equally well to both batch processing and real-time measurements.

Keeping this in mind, reasonable output levels were acquired by modifying Equation 12. If, after each addition, the output were scaled down by a certain factor, increasing repetitions would not cause any growth in the output level. The equation was therefore modified to provide stable characteristics,

$$Y_{(N,M)} = \sum_{r=1}^{M} \left(\frac{X_{(n,r)} - Y_{(n,r-1)}}{r} + Y_{(n,r-1)} \right) n = 1, \cdots, N \quad (13)$$

where $X_{(n,r)}$ is substituted for the input term $w_{1(n,r)}$ and, $Y_{(n,r-1)}$ is substituted for the input term, $w_{2(n,r)}$ which is the sum of the repetitions prior to the r-1th recursion. This equation was applied in the system simulation, which provided efficient system dynamics. Fig. 3 shows the result of a real-time measurement; the noisy input, and the averaged output after a 2000 recursions of averaging process.

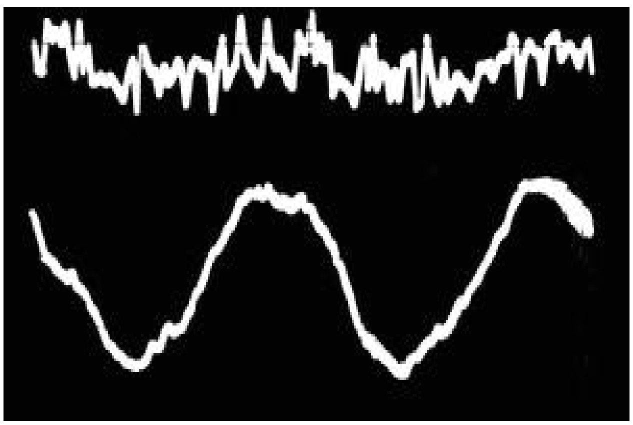

Fig. 3 Photo of a real-time measurement. Only noisy input and the averaged output are shown.

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was born in Kars, Turkey. He received the Sc. B degree in electrical engineering from Gazi University in Ankara in 1979, and Candidatus Magisterii and Candidatus Scientiarum in Informatics from University of Oslo in Norway, in 1984 and 1987 respectively. He joined the National Institute of Technology in Norway in 1987. In 1989 he joined The Center for Information Technology at the University of Oslo/Norway, and worked there for 7 years. During this period he has published two textbooks about UNIX and Shell Programming, and concentrated at computer simulation and digital signal processing and their application to medical signal processing Süleyman Kondakci is an experienced IT security researcher with 18 years of experience in distributed information systems and IT security test and evaluation. Kondakci has been assigned to National Research Institute of Electronics and Cryptology (NRIEC) at the Scientific and Technical Research Council of Turkey (TUBTAK), where he specialized in conducting security of mission critical systems. Among other tasks, he has founded and managed Information Security Laboratory at NRIEC-TUBITAK. Kondakci is currently assigned at the Department of Computer Engineering, Cankaya University. Recently, he has worked extensively on projects to develop IT security procedures and mechanisms for demanding IT environments. He is also the designer of the "Security of Distributed Object Systems" for NATO INFOSEC Framework.